Stress-life criteria for fatigue assessment of structures: advantages and drawbacks

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Abstract

Presently in rules for fatigue assessment of steel, and in particular, welded structures in different technologies subjected to intensive alternating service loading the Stress-Life (S-N) criteria are recommended in several versions of approaches. These are the Nominal stress approach based on typifying welded joints and representing fatigue resistance of the joints by classed S-N curves; the Hot-spot stress approach focused on evaluation of κstructuralњ stress by the means of finite-element analysis (FEA) and the Notch-stress approach based on the FEA-based assessment of the local stress caused by the geometry of structural detail and the weld shape. The criteria and approaches provide assessment of fatigue properties of structures, however, accompanied with a series of approximations and uncertainties. The nature of drawbacks of the S-N criteria and approaches is commented and feasible means of improvement the fatigue criteria evaluation and applications in fatigue assessment procedures are proposed.

1 Introduction

The Stress-Life (S-N) criteria are recommended presently in rules for fatigue assessment of structures subjected to intensive alternating service loading in versions (approaches) differing mostly by the procedure of considering effects of stress concentration in critical locations. [1, 2, 6], etc. The approaches are supplemented with the linear damage summation rule to consider random character of service loading in fatigue analysis of structures. The criteria and approaches were derived aimed at a non-complicated application in practical problems; however, a series of drawbacks and inaccuracies of those was being noted. Firstly, the experimentally obtained data base Џ S-N curves - providing evaluation of fatigue properties of structures was collected by testing of κclassedњ (including typified welded joints, as in the case of the Nominal stress approach [6]) specimens under cyclic loading terminated at almost complete failure (κseparation in two partsњ). This was leading to uncertainties in considering fatigue properties of materials in welded joints, effects of residual welding stress, definition of the state of damage in structural components, crack size, corresponding exhaustion of fatigue life. Further, recommendations for testing specimens comprising typified welded joints which were aimed at considering effects of materials of the joint (weld material, material of fusion zone, etc.), of residual welding stress, implemented in the data base did not provide identity of fatigue damage between specimens and structural details. Partly, it was because of diversity of geometry of structural details comprising кtypifiedњ joints, which was recognized decades ago. Development of the finite-element analysis (FEA) facilities allowed analyzing the stress field in actual structural details, in particular, stress at critical locations. These facilities [3] and experience of strain measurement in welded components [4] were used to derive the Hot-spot stress approach (HSS) [1, 2], etc. The approximate estimation of the local stress caused by the particulars of the stress flow at the welded joint in HSS, necessity to account for the effects of geometry of the weld itself, resulted lately in development of the Notch stress approach [5], etc. Assessment of local stress causing the damage process allowed reducing the range of the design S-N curves to those presenting properties of the base and weld material only. However, apart from solving the problem of effects of geometry of structural detail on the damage process, the mentioned above disadvantages were not corrected. The above criteria and approaches are commented in more details in the below focused on problems of practical application and certain remedial actions are proposed.

2 Introduction

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3 Stress-Life Approaches

The current S-N (Stress-Life) approaches to fatigue analysis and design of structures, e.g., [6], are based on assumption that material of structure nominally deforms elastically in service loading conditions. Respectively, in the range of fatigue lives between $10^4 \leq N(S) \leq (2\ldots5)10^6$ (the left-hand figure is related to the above statement, and the right-hand one corresponds to the long-established practice of assessment the fatigue limit stress in mechanical engineering) the **S-N** curve is usually approximated in logarithmic coordinates by the straight line, equation if which is given by the BasquinŠs formula (1910):

$$N(S) = C/S^m, \tag{1}$$

where S is the stress range, C and m are the кmaterial constantsњ, m is the S-N curve кslope parameterњ. The range of endurances of the design S-N curves is limited from the left side, as said, by the number of cycles prior to failure equal to , which approximately corresponds to the nominal stress amplitude around the yield stress.

Damaging effects of stress amplitudes below the conventional fatigue limit stress in service irregular loading histories is considered by the кtwo-slopeњ shape of S-N curves and by introducing the кcut-offњ fatigue limit stress, substantially lower than the conventional one, fig. 1 [6].

The mechanics of fatigue damage of welded joint materials is implied (not definitely specified) as built into the design S-N curves based on analysis of results of fatigue testing of specimens comprising the typified (classed) welded joints, e.g., shown in fig. 2.

The base and weld material mechanical properties are not specified, and the S-N curves uniquely represent fatigue properties of a range of structural steels supporting the so-called кNominal stress approachњ, as shown in fig. 1, whereas it is known that fatigue strength of steels is approximately proportional to the ultimate strength [7], although resistance of welded joints may depend substantially on the mechanical properties of the electrode material. The scheme of evaluation of the nominal stress in example of a bracket welded to the flange of stiffener in ship structure (fig. 2) is shown in fig. 3.

Specific of the testing specimensŠ procedure is automated termination of test when initiated and growing fatigue crack notably affects the specimen compliance preced-

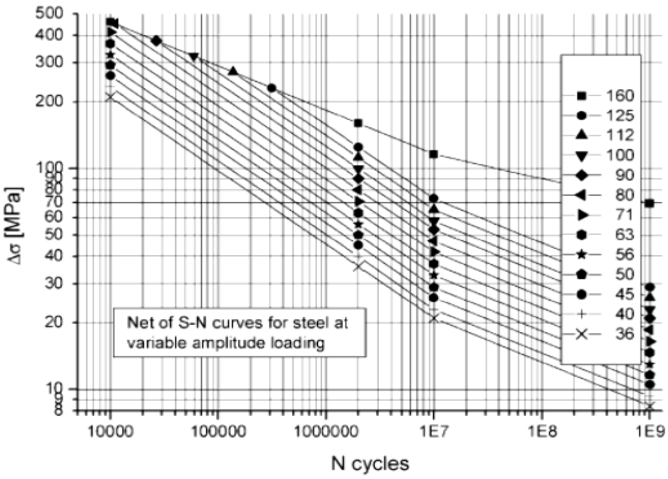

Figure 1: IIW classed design S-N curves for structural steels [6]

ing complete fracture in two parts. Therefore, the test result, the number of cycles by the test completion includes, roughly, a portion of life until the macroscopic crack origination and a part when crack propagates from the origination site. Respectively, when the approach is applied to assess fatigue resistance of a structural detail, the state of damage, corresponding crack size, occurs uncertain what attracted attention of experts (e.g., [5, 8, 9]). Fig. 2 shows a specimen with typified welded joint (one-side attachment) and a structural detail (in ship bottom structure) attributed to the same type of the joint. It may be seen a resemblance but not the identity between the specimen and detail, especially when the geometry and the crack extension particulars would be mentioned. Attempts were made to develop procedures which might have assisted in establishing the fatigue identity of welded joints in structural detail and respective test pieces and design S-N curves [8, 9]; however, the suggested procedures were substituted by implementing other approaches.
What is important, fatigue tests of typified welded joins at cyclic loading were being carried up with positive load ratio (ratio of the minimum to the maximum load in the cycle) to avoid buckling in the compressive part of the load cycle. This means the design S-N curves are related to the mentioned type of loading. Lately, attempts were made to consider in fatigue analysis of structural details effects of different loading conditions [10]. Meanwhile, loading asymmetry plays secondary role in the crack initiation phase which is controlled almost completely by the stress ranges, excursions causing slip processes in material microstructure [7, 12], etc. When the crack is initiated its further extensions substantially depend on the tensile part of alternating loading. Respectively, since a substantial portion of fatigue life of specimens represents the crack growth, it introduces additional uncertainty into the results of fatigue analysis of structural details.
The briefly mentioned disadvantages of the Nominal stress approach promoted development and application in practice of the Hot-spot stress (HSS) [1, 2], etc., and latterly, of the Notch-stress approach (NSA) [5], etc. These approaches are supported by respective Stress-life criteria, addressed to avoiding ambiguity in establishing the identity between classed welded joints and actual structural details, and providing considering effects of stress concentration in structural details by the finite-element

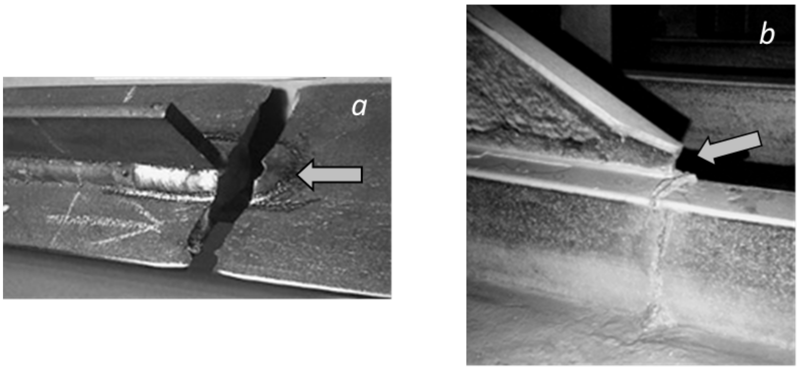

Figure 2: a) - Fractured specimen, FAT63 Class (Fig.1); b) - Crack in a ship structural detail identified as FAT63 (Courtesy B.Purtle, LloydŠs Register of Shipping, UK)

analysis. With regard to the principles of the HSS and the NS approaches the set of design S-N curves is reduced to those of the base material and material of welded joint (butt-welded joint), completed with the design curves for details in corrosive environment [10].
In HSS approach the stress at a critical location, typically at the weld toe, as show arrows in Fig.2, has to be found by extrapolating stress in element centroids towards the weld toe, fig. 3; by this the stress raise is assumed caused by the shape of structural detail and the role of the weld bead geometry is related to properties of the respective S-N curve (class D curve, butt-welded joint). Substantially fine meshing of the welded detail model in the NS approach allows obtaining local stress at the weld toe considering, both, effects of the detail and the weld bead geometry, as schematically shown in Fig.3; at the same time it is assumed that at the weld toe there is a smooth, radiused, transition from the parent to the weld material [5]. Such assumption is based on physics of liquid metal contact with the solid where meniscus appears.
So far, effects of stress concentration in critical locations of structure in the HSS and NS approaches are considered by multiplying the nominal stress range by the respective stress concentration factors or calculation local stress using, as said, the finite-element technique.

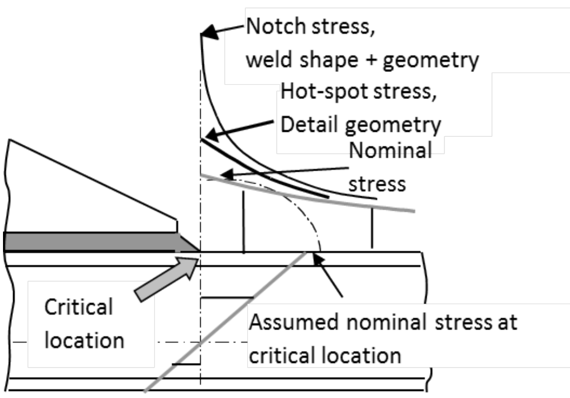

Figure 3: Assessment of characteristic stress for fatigue analysis of structural details

Fig. 4shows the types of meshing of the bracket ending in ship structure (fig. 2,b, fig. 3) designed for application of the mentioned approaches. The mesh type in fig. 4,a is attributed to the Hot-spot stress approach; its design follows the principle кt x tњ, t is the flange thickness and the size of finite elements at the bracket ending [9]. Another mesh, fig. 4,b, fits the requirements of the FE modeling when the Notch-stress has to be applied: the element size at the weld toe is 0.2 of the assumed weld toe radius [5].
It should be emphasized that assessment of the local stress in these approaches is based on assumed linear elastic material behavior in critical locations. Referring further the characteristic stress to the classed S-N curve makes rather an illusion of proper assessment of damage.

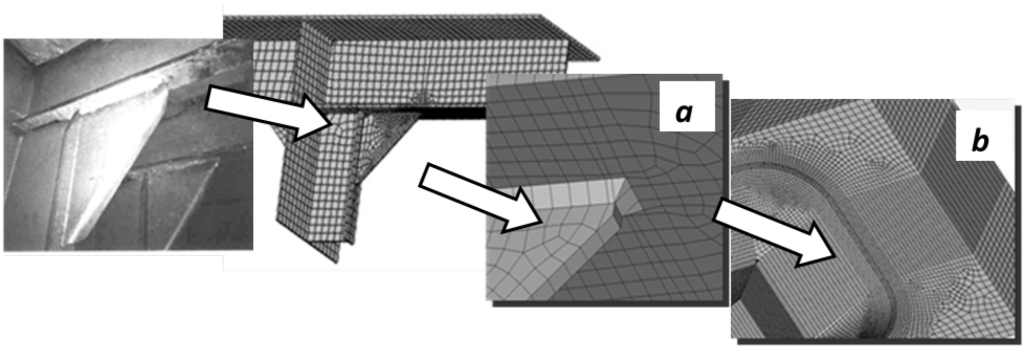

Figure 4: Structural detail and examples of FE meshes designed for application of the HSS (a) and the HSA (b) approaches [11]

In fact, it means evaluation of the damage with uncertainty, although somewhat on the conservative side. In the high-stress range of the service loading the input of this over-estimation of fatigue damage in the total sum might be regarded insignificant due to stochastic properties of excitation and relatively infrequent intensive loading of structures. Whereas at the moderate service loading, in the high-cycle regime, which provides the predominant damage, the above approaches neglecting the effects of material microplasticity at critical locations, may substantially over-estimate the damage.
Comparative analysis of fatigue properties of ship structural detail shown in fig. 4, кPost-Libertyњ dry cargo ship, non-specified wave climate, upper deck structure amidships [11], resulted in substantially differing values of fatigue damage related to 20 years of ship service: application of the HSS approach indicated D = 1.24, whereas the Notch-stress approach use shown the damage index as D = 0.54, and the Strain-life approach, where the inelastic behavior of material was accounted for, resulted in D = 0.35. The mentioned comparative study just illustrates the problem; perhaps, a comprehensive analysis might be needed. However, firstly, the apparent disadvantages of the current Stress-life methodologies should be corrected. First, the Hot-spot stress approach barely might be improved: the prospects of perfection of the technique of evaluation the hot-spot stress are not seen, receipts for design the FE model of welded detail barely allow for considering material inelastic behavior, the crack size, residual welding stress is accounted for fairly approximate.
The feasible means of improvement of the approaches and S-N criteria might be

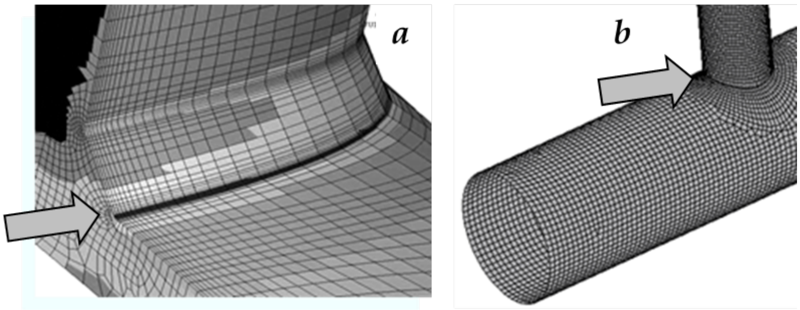

Figure 5: FE-models of tubular welded joints: a) Џ model developed for fatigue analysis with Strain-life approach [13]; b) Џ model of the joint for the HSS aided analysis [15]. Arrows indicate the critical locations

focused mostly on the Notch stress approach and be the following:

- In formulation of the S-N criteria fatigue testing of specimens has to be carried out until origination of macroscopic crack. It would need in application of the well developed methods and technique of crack detection and in respective improvement of the test procedure,

- Fatigue testing reasonably should be carried out at symmetrical loading, so that when necessary effects of mean stress on the damage might be reasonably accounted for,

- Approximate considering the inelastic cyclic behavior of the critical location material by correction of the local stress with the means of the notch factor value, e.g., formulated by Peterson [14]:

$$K_f = 1 + (K_t - 1)/(1 + g/r), \tag{2}$$

- where K_t is the theoretical stress concentration factor, g is "material structure" parameter, according to [14], this parameter for structural steels with the yield strength in the range of 235-390 MPa may be estimated by $g = 0.38(350/\sigma_u)$, where σ_u is the ultimate strength of material, r is the notch root radius,

- As to the effects of residual welding stress it may be assumed part stress relaxation at the very crack initiation phase due to the cyclic plasticity of material accentuated at the critical location.

The Notch stress approach may be completed by the procedure of evaluation of the crack initiation and extensions by further development of the damage accumulation principle suggested in [13, 16, 17], etc., complemented by designing the finite-element models of structural components with the necessary fineness of the mesh at critical locations and in the plane of expected crack growth, e.g. as shown in fig. 5,a. Material (finite) elements should be deigned small enough to neglect the stress and strain gradients through the element, but large enough to apply the continuum mechanics format.

Let the number of load cycles corresponding to crack initiation in themost stressed elements along the notch root (weld root as in fig. 4,b, 5,a) is ; then damage accumulated at this step in the surrounding elements:

$$d_{initial} = N_0/N_i \tag{3}$$

So far, $n_i = N_0$ is the initial part of the кfatigue processњ, N_i is the number of load cycles to failure in the successive stress range conditions, in every consecutive кmaterial elementњ where stress range prevailed the non-damaging level (cut-off fatigue limit stress) in the initial and sequential loadings, which develop due to кfailureњ of elements. The кfailureњ is defined by the condition:

$$d = d_{initial} + \sum(n_i/N_i) = 1 \tag{4}$$

Here $n_i = n_i(S_i)$ is the number of load cycles corresponding the stress range S_i, which completes the damage accumulation in a particular FE (кmaterial elementњ), d, at every кcrack extensionњ. - As said in above, effects of residual welding stress may be insignificant in the crack initiation phase and neglected; however, in analysis of the crack extensions the residual stress influence cannot be ignored and should be considered in dependence on the redundancy of structure.

I should be noted, the procedure would need in rearrangement of the mesh (automated procedure is presently provided by the FE software) and stress field assessment at every crack extension through successive finite elements (кmaterial elementsњ).

The approach would make feasible fatigue analysis of the damage process commencing from initiation of service loading through the crack initiation at a structural discontinuity and growth until onset of a critical condition, e.g., until the through crack in a pipe line (e.g., [13, 16], etc.).

What may be regarded promising, the damage accumulation model may be complemented by the crack growth model given by the Linear fracture mechanics (LFM) principles, e.g. [18], which would allow for predicting conditions for the instable fracture of a structural component. The approach was successfully tested in several examples where the crack extensions in fillet-welded joint were simulated [16], in analyses of crack growth in test specimens [17]; results of numerical simulation were in good agreement with the test data.

4 Conclusions

The Stress-Life (S-N) criteria applied in the Nominal stress approach, Hot-spot stress and Notch-stress approach provide assessment of fatigue properties of structures accompanied with a series of approximations and uncertainties. The most substantial drawbacks of the S-N criteria-based techniques of fatigue analysis are the problems of identity of damage between classed specimens and actual structures, considering effects of stress concentration in structural details, uncertainty of the crack size corresponding completion of estimated fatigue life of a structural component, etc. Several means of improvement of the Notch-stress approach and respective S-N criteria are suggested proved by results of a series of studies.

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References

[1] Paetzold, H., Fricke, W., Petershagen, H. Fatigue Assessment of Welded Ship Structures based on Hot-Spot Stresses. Seminar on Fatigue of Welded Structures. IPME RAS, St Petersburg, 25-27 Sept. 1992

[2] Niemi E., Fricke W., Maddox S.J. Structural Hot-spot Stress Approach to Fatigue Analysis of Welded Components. DesignersЎ Guide. Int. Institute of Welding, IIWЏDoc. XIIIЏIWG3Џ31r1Џ14 Cambridge. Abington. 2015. P.49

[3] Marshall, P.W. Basic Considerations for Tubular Joint Design in Offshore Construction. WRC Bulletin 193. 1974. New York

[4] Haibach, E. Die Schwingfestigkeit von Schweib Verbindungen aus der Sicht einer Ortlichen Beanspruchungsmessung. Laboratorium fur Betriebsfestigkeit (LBF), Darmstadt, Report FB-77, 1968 (in German)

[5] Fricke, W. Guideline for the Fatigue Assessment by Notch Stress Analysis for Welded Structures, IIW-Doc. XIII-2240r1-08/XV-1289r1-08 Cambridge. Abington. 2008.

[6] EUROCODE 3: Design of Steel Structures. Part 1-9: Fatigue. BS EN 1993-1-9: 2009. P. 36

[7] Frost, N.E., Marsh, K.J., Pook, L.P. Metal Fatigue. Clarendon Press, Oxford. 1974

[8] Petinov, S.V., Thayamballi, A.K. The Application of S-N Curves Considering Mismatch of Stress Concentration between Test Specimen and Structure. Journal of Ship Research, Vol.42, No.1, 1998, p.68

[9] Petinov, S.V., Reemsnyder, H.S. and Thayamballi, A.K. The Similitude of Fatigue Damage Principle: Application in S-N Curves-based Fatigue Design. In: Fatigue Design and Reliability/ Ed. By G.Marquis and J.Solin. ESIS Publication 23. Elsevier Science Ltd., 1999, pp.219-228

[10] Det Norske Veritas. Fatigue Assessment of Ship Structures. Classification Notes є 30.7. 2010. Hovik, Norway

[11] Petinov, S.V., Afanasyeva, I.M. Fatigue Assessment of Structures in High-cycle Segment: Technique and Problems. Proc., The XXXVII Intern. Summer School - Conference кAdvanced Problems in Mechanicsњ APM-2010, SPb-Repino, 2010. pp. 519-525

[12] Petinov S.V. Fatigue Analysis of Ship Structures. Backbone Publishing, NJ. 2003. P. 262

[13] Petinov, S.V., Guchinsky, R.V. Fatigue Assessment of Tubular Structures // Magazine of Civil Engineering (Инженерно-строительный журнал) No1 (36), 2013, pp. 39 Џ 47. ISSN 2071-4726

[14] Peterson, RE Stress Concentration Factors. A Handbook. J.Wiley and Sons, New York. 1977, p.301

[15] Conti, F., Verney, L., Bignonnet. A. Fatigue assessment of tubular welded connections with the structural stress approach, кFatigue Design 2009њ. 25-26 November 2009. Senlis, France, pp.1-8

[16] Petinov, S.V., Guchinsky, R.V. Fatigue of a Fillet-welded Joint Assessment by the FEA Simulation of Damage Accumulation // Magazine of Civil Engineering (Инженерно-строительный журнал) No 4 (22), 2011, pp.5-9 ISSN 2071-4726

[17] Imran, M., Siddique, S., Guchinsky, R.V., Petinov, S.V. and Walther, F. Comparison of fatigue life assessment by analytical, experimental and damage accumulation modeling approach for steel SAE 1045. Fatigue and Fracture of Engineering Materials and Structures, 2016, pp.1-29.

[18] Guchinsky, R.V., Letova, T.I., Petinov, S.V. Modeling of Fatigue Process by Combining the Crack Initiation and Growth / Proc., The XLII Intern. Summer School - Conference кAdvanced Problems in Mechanicsњ APM-2014, SPb-Repino, SPb, IPME RAS, 2014, pp.128-134.

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